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Refined Source Terms in WAVEWATCH III with Wave Breaking and Sea Spray Forecasts

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Ocean Wave forecasting relies on using a non-phase resolved spectral model to forecast the complex wave field. While advection plays an important role, the models rely heavily on 3 source terms: the Snl - the non-linear source energy transfer term, Sin - the input of energy to the wave field from the winds, and Sds - the wave dissipation source term which transfer wave energy to the currents and turbulence.

In this talk we discuss the development of new input and dissipation source terms, as part of an ONR funded NOPP program, to incorporate recently developed physics into the operational wave models. The input source term includes the effects of sheltering of the input to smaller waves by larger waves, as well as known physical constraints such as drag coefficient. The dissipation term is based on a thresholded breaking wave energy dissipation term, with background turbulence, and is used to forecast the breaking crest length per unit area, and the total energy dissipation. These are compared against observations, and forecasts are made out to 100 m/s.
Using a suite of models to define multiple scales associated with coastal sand transport around complex reefs

Cyprien Bosserelle, Shari L. Gallop, Charitha Pattiaratchi and Ivan D. Haigh

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Field measurements suggest that coastal reefs cause strong spatial variability in sediment transport pathways. A suite of numerical models over multiple spatial scales was used to investigate the sediment transport processes around complex reefs at a perched beach in Western Australia. The multi-scale methodology focused on the simulation of tides, storm surges and waves from the: (1) ocean basin and continental shelf scale (using the Wave Watch 3 model for the whole of the Indian Ocean basin for waves and the MIKE 2DH barotropic model for tides and storm surges); (2) the regional scale (SWAN model for waves); (3) the coastal scale (Xbeach for morphology) and (4) the single wave scale (Smoothed Particle Hydrodynamics, SPH model). The model outputs of sea level and realistic directional wave spectra were used to force the XBeach morphological model at the coastal scale. The transition between spatial scales allowed the conservation of wave spectral information and therefore provided a realistic forcing to the coastal model. The simulations revealed dramatic wave dissipation over the offshore and coastal reefs allowing only a fraction of the wave energy to reach the coast. The XBeach model was used to estimate the maximum erosion likely to occur during a single extreme storm. The single wave scale shows the resuspension events due to the wave breaking near the reef forming a scour step in front of the reef. This multi-scale approach resolved the spatial variability in the sediment transport pathways around the reefs.
The success of many marine mollusc species is strongly dependent upon hydrodynamic conditions that retain or transport larvae to favourable settling grounds. To effectively manage these fisheries, it is therefore essential to understand the dominant physical processes that control the hydrodynamics in these regions. In Shark Bay, Western Australia longitudinal density gradients drive gravitational circulation that is important for bay-ocean exchange and transport of biological matter such as larvae. In this inverse estuary higher salinity water is exported through the two main entrance channels at depth and is replaced by lower salinity ocean water at the surface. Recent winter field experiments in Shark Bay’s entrance channels recorded dense water outflows that varied in intensity and frequency between the two main entrance channels. The outflows occur during periods of low tidal mixing which allows for the vertical water column to be stratified and thus can be predicted in advance. The General Estuarine Transport Model (GETM), a three-dimensional baroclinic hydrodynamic model, was used investigate the spatial variability of the dense bottom water outflows and the inhibiting effects of mixing by tidal currents and wind. The model results indicated well-defined transport pathways consistent with the field measurements. The outputs from the hydrodynamic model were used to drive a passive particle dispersal model, to simulate the dispersal of scallop larvae and establish source-sink relationships between stocks. We found that stocks near to the entrance channels were susceptible to flushing by the dense water outflows and that a hydrodynamic ‘barrier’ existed between the southern and northern regions of the Bay. These results support the practice of treating the two areas as separate spawning stocks and will aid in fisheries management decisions. More broadly, the results support the hypothesis that the main pathway for the export of hypersaline bay water and biological material such as larvae is out of the northern entrance to Shark Bay, and that density-driven bottom currents likely play a major role in exchange between the bay and ocean.
Sea breezes force near-inertial waves close to the critical latitude for resonance

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Inertial oscillations are anti-cyclonic motions at the local inertial frequency and are observed globally in regions with weak frictional damping. Near the latitudes 30° south and north the inertial frequency is approximately diurnal. Periodic forcing at these ‘critical latitudes’, by tides or diurnal variations in wind stress, can cause a resonant response in the currents. Observations from the WAIMOS Two Rocks shelf and slope transect mooring array, located near the critical latitude for resonance, reveal strong anti-cyclonic circular motions that often exceed the mean Leeuwin current speeds by > 0.3 m s\textsuperscript{-1}. The observations were made in a region of particularly low tidal energy, therefore the resonant response of the currents is purely driven by the diurnal sea breeze system. As a result, the influence of the wind was observed to depths > 250 m (much larger than then the Ekman depth of \sim 70 m). The sea breeze system in south-western Australia is one of the strongest worldwide, frequently exceeding 15 ms\textsuperscript{-1}, and contributes to 35% of all wind patterns annually. Consequently, in the absence of significant tidal mixing, the sea breeze forcing of near-inertial waves in this region is an important candidate for vertical mixing across the pycnocline.
We used a two-dimensional, barotropic, numerical model to examine the complex behaviour of the tides in Bass Strait. Bass Strait, located in south-east Australia between the Australian continent and Tasmania, has the appropriate dimensions to create a half-wave tidal resonance for the $M_2$ tides. The $M_2$ tidal wave (amplitude < 0.4 m) enters the strait from both strait openings, increasing the $M_2$ tidal amplitude towards the central northern Tasmanian coast to a maximum of ~1.1 m. The tidal phases and current ellipses in the strait showed the $M_2$ tides resembled a half-wavelength resonance in a curved, open basin. The semidiurnal, $S_2$, and diurnal, $K_1$ and $O_1$, tidal amplitudes were comparatively small (< 0.2 m), progressive in nature and mostly constant through the strait. The model simulations revealed that when only open boundary tidal (OBT) forcing was included in the model, the model over predicted the $M_2$ amplitudes by ~10–15% in the strait’s central region; however, when OBT and direct gravitational tidal (DGT) forcing were included, the model accurately reproduced the observed tidal amplitudes. DGT forcing was used to generate resonantly amplified $M_2$ tides (amplitudes of 0.1–0.3 m) locally, with destructive interference between the OBT-forced and DGT-forced tides occurring in the centre of the strait. The model simulations also revealed that storm systems propagating west to east attenuated the $M_2$ tidal amplitudes within the strait. The greatest decrease in the tidal amplitudes occurred along the central northern Tasmanian coast and was attributed to tide-surge interaction and resonance behaviour in the strait.
Modelling meso-scale dynamics along western and southern Australian shelf and slopes: A ROMS modelling approach

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As part of a study on “ocean-shelf exchange with an emphasis on the roles of waves, tides, eddies and cross-shelf flows on carbon exchange”, funded through ANNIMS, a three-dimensional (3D) model was configured to include the western and southern Australian shelves, slopes and the adjacent deep ocean using the Regional Ocean Modelling System (ROMS). The model domain, extending from the Kimberley to Bass Strait, uses curvilinear-orthogonal grids with 2-4 km horizontal resolution for the entire region with 1-2 km resolution in the sub-domains (north-west, central-west and south-west) with 30 sigma layers in the vertical water column. The model was forced with daily atmospheric (wind and air pressure) and air sea fluxes (heat and freshwater). The model open boundaries were specified with monthly salinity and temperature climatology. The model forcing included tides and monthly mean sea levels. The model initial and forcing data (2000-2010) were extracted from various global and Australian oceanographic/meteorological data sources and interpolated into surface horizontal mesh and open boundary vertical sections.

In this presentation, we highlight the major physical processes in the region using ROMS model output. The model is able to reproduce the tidal characteristics, major surface and sub-surface currents systems (e.g. Leeuwin Current, Leeuwin Undercurrent, Capes current etc.), and associated eddy fields. The model also reproduced the seasonal processes such as: summer upwelling along Ningaloo and the Capes region, dense water formation and cascading in the central western Australian shelf. The model predicted surface currents were compared with HF radar data (Perth region) and cross-shelf flows with current meter moorings. Model predicted SST and SSH was compared to satellite measurements.

We have also examined the contribution from different forcing agents on physical processes in the region by including and excluding different model forcing terms or assigning forcing variable to constant value or zero. We found that the distribution of atmospheric pressure (in addition to other forcing agents) also significantly influences the strength of southward flowing currents (e.g. Leeuwin current). Currently we are in the process of coupling the physical and biogeochemical ROMS model to study the influence of these different processes on the shelf carbon exchange process.
The seasonal cycle of sea level (SCSL) is highly variable around the coast of Australia in terms of annual amplitude and timing of maximum level and has been investigated using monthly mean sea level (MMSL) datasets from satellite altimetry, tide gauges and a barotropic hydrodynamic model for the period 2000 to 2010. We used the Danish Hydraulic Institute’s MIKE21 FM (flexible mesh) suite of modelling tools with the grid resolution chosen based on the region’s coastal topography and local water depth variability and with a resolution of ~20–30 km at the open ocean boundaries, decreasing to < 2.5 km along the whole Australian coast. The model was forced using astronomical tidal levels, from a global tidal model (TPX07.2), and meteorological fields, from a global reanalysis (NOAA/NCEP).

The annual amplitude of SCSL exceeds 0.3 m in the Gulf of Carpentaria and peaks in January and is a minimum in July. In this region the barotropic signal accounts for more than 80% of variability. Our model results with different model extents clearly showed the open boundary extent is extremely sensitive for capturing the barotropic (wind setup) signal, particularly in the Northern part of Australia. The model domain extended up to Banda and Java Seas accurately captured the barotropic seasonal signal in Gulf of Carpentaria. The model results showed a significant barotropic SCSL with amplitude ~0.1 m occurs along the eastern Great Australian Bight and peaks in August-September.

The altimeter data and model output have been combined to map the distribution of the barotropic and baroclinic monthly mean sea level (MMSL) and seasonal cycle of sea level around Australia. The estimated baroclinic signal (altimeter minus barotropic model) was compared with steric heights derived from temperature and salinity climatology obtained from the World Ocean Atlas (WOA-09). Our analysis showed the annual steric amplitude and its phase speed along the western and southern Australia is strongly correlated to the strength of the barotropic signal in northern Australia.
Observations and Modeling of the North West Shelf of Australia during Austral Summer 2011/2012

Jeffrey W. Book¹, Jennifer Ayers², Richard M. Brinkman³, Derek M. Burrage¹, Philip Chu¹, Gregory N. Ivey⁴, Nicole L. Jones⁴, Samuel Kelly⁴, Ryan J. Lowe⁴, John Luetichford⁴, Charitha Pattiaratchi⁴, Matthew D. Rayson⁵, Ana E. Rice⁵, James Richman¹, Clark Rowley¹, Craig Steinberg³, Peter Strutton²

¹Naval Research Laboratory, ²University of Tasmania, ³Australian Institute of Marine Science, ⁴University of Western Australia, ⁵National Research Council

During the austral summer of 2011/2012, a series of collaborations between U.S. and Australian funded projects led to the collection of a large observational and modeling dataset for the North West Shelf of Australia. Key collaborations included the Naval Research Laboratory’s (NRL) “AUV Data Analysis for Predictability in Time-Evolving Regimes” (ADAPTER) project focused on methods for preventing operational data aliasing due to internal tides during data assimilation, the Australian Research Council funded project on “Coupled physical and biogeochemical dynamics on the Australian North West Shelf”, and the Office of Naval Research Global funded project on “The connectivity of the Australian North West Shelf with the Leeuwin Current”. The observational plans for these three projects were integrated with the Integrated Marine Observing System (IMOS) Australian National Mooring Network arrays for Ningaloo and Pilbara, and were coordinated with observing plans for the Western Australian IMOS node.

These partnerships resulted in the deployment of 30 moorings at 23 different sites and 5 AUV gliders for various intervals of measurement between November 2011 and August 2012. The measurement program peaked during April 2012 when almost all of these resources were still deployed and a series of cruises by the R/V Solander collected 120 CTD and 318 microstructure profiles. In addition to the observational field work, NRL ran a high resolution version of the Naval Coastal Ocean Model (NCOM) for the North West Shelf and further model runs of both NCOM and the Regional Ocean Modeling System (ROMS) are planned. Analysis of this large dataset has just begun.

Early results show the expected occurrence of strong non-linear internal tides throughout the area. To begin work on ADAPTER research goals, an extended empirical orthogonal function analysis was applied to mooring data allowing the description of fully non-linear internal tide packets with only a few modes of variability and describing the spring/neap cycle of packet evolution. By projecting glider observations on these modes, the spatial and temporal components of the variance can be separated allowing for estimation of the underlying mesoscale features desired for data assimilation. Future analysis is planned to test these and other data assimilation methodologies with this dataset and to focus on the other primary research questions of the collaborating projects.
Dense Shelf Water Cascade (DSWC) on the Rottnest Continental Shelf in South-western Australia

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Temperature and salinity (and associated density) data collected using autonomous shallow water Slocum ocean gliders along the Rottnest Continental Shelf, revealed the formation and propagation of dense water masses which is defined as dense shelf water cascade (DSWC). DSWC is a common occurrence in shallow depths of the shelf (<50m) and continues throughout the year with varying degrees of intensity. The region experiences a Mediterranean climate with hot summers and cold winters. During the summer months the inner continental shelf waters increases in salinity due to evaporation. In winter as this higher salinity waters cool and its density is higher than offshore waters and a gravitational circulation is set-up where the inner shelf water are transported as higher salinity plumes into deeper waters. The density currents are estimated to be ~1-2 cm/s, which are similar to those measured in other similar regions globally. Slocum ocean glider data obtained in 2009 and 2010 (41 transects) indicated that there is a cross-shelf density gradient with higher density water inshore throughout the year providing the mechanism for the DSWC. However, the DSWC is controlled by wind action: during the summer regular strong wind events due to persistent sea breezes results in no vertical stratification thus an absence of DSWC. In contrast, during autumn and winter DSC, is a regular occurrence interrupted by storm events. The DSWC plays an important role in cross-shore exchange of water and material in Rottnest Continental Shelf.
The Australian Coastal Ocean Network, ACORN.

Lucy Wyatt, Sven Rehder, Arnstein Prytz, Alessandra Mantovanelli, Jasmine Jaffrés, Mal Heron and Dan Atwater

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This poster will provide an overview of the IMOS ACORN facility and the data it provides. Methods that have been, or are being, developed to improve the quality of these data and increase availability will be discussed. Some examples of applications of the data will be presented. This will include a number of particle tracking and coral reef management applications in the Great Barrier reef. Some work on wave measurement, in particular directionality, will also be described. Potential applications, using examples from systems elsewhere in the world, will be outlined.
Statistical modelling of ocean variability on the southeast Australian continental shelf

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There is a scarcity of spatially and temporally homogenous measurements of ocean variability on the Australian continental shelf. The ocean reanalysis product Bluelink ReANalysis (BRAN) provides estimates of ocean variability around Australia at 1/10 degree resolution. BRAN reproduces the large-scale patterns of sea surface temperature (SST) in deep water, such as those associated with the East Australian Current and the Leeuwin Current, but performs poorly over the continental shelf. We have developed a linear statistical model to more accurately estimate in-shore SST using off-shore SST from BRAN. SST variability is separated into the mean, seasonal cycle, and the residual variability and separate models are developed for each component. The off-shore locations used to inform the model are determined by jointly taking into account (i) the quality of BRAN at each location, (ii) the strength between the in-shore and off-shore variability, and (iii) the proximity of the in-shore and off-shore locations. Model performance is demonstrated at a point location in Bass Strait and then it is extended onto the continental shelf around southeastern Australia. We will discuss the regional variation in model performance as well as the role of the large-scale circulation in providing accurate predictors on on-shore SST. We will also discuss the possibility of applying the model to dynamically downscaled future ocean projections of the 21st century.
Development and application of ROMS based models for the South Australian region.

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Funded by the South Australian State Government ($620K) through Marine Innovation South Australia (MISA) the Hydrodynamic, Wave and Biogeochemical Modelling Facility was established in 2007 at SARDI Aquatic Sciences. Building on oceanographic data streams from the South Australian Integrated Marine Observatory System (SAIMOS), the facility has developed a suite of ROMS (Regional Ocean Modeling System) -based models to provide cost-effective scientific solutions for researchers, industry and government agencies. Here we present an overview of the primary shelf and coastal observing systems and hydrodynamic models developed for the South Australian region including; the South Australian Regional Ocean Model (SAROM) and a nested high resolution Spencer Gulf model (SGM). Examples from the hydrodynamic models coupled with wave (SWAN), biogeochemical (NPZD Fennel) and particle tracking (LTRANS) sub-models are shown to demonstrate how developments in multi-disciplinary ocean modelling are helping to deliver sustainable growth and management of aquaculture, fisheries and marine resources in South Australia. These include applications to determine the sustainable carrying capacity of aquaculture and the optimisation of harvest strategies for the western king prawn fishery in Spencer Gulf, South Australia.
The evolution of a Cold-Core Eddy in a Western Boundary Current

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Cold-Core Eddies (CCEs) are a common feature in Western Boundary Currents such as the East Australian Current (EAC). We use The Regional Ocean Modelling System to investigate the ocean state during the formation of one such CCE in the EAC during October of 2009. This eddy initially appears as a small billow which cuts into the edge of the EAC. We make use of particle release experiments to investigate the eddy’s source waters. Nearly all of the surface particles within the eddy (and hence source waters) originated on the continental shelf. Particles above 500 m within the eddy came from both north (as expected) and south of the eddy. Particles come from the south due to a northward flow on the continental shelf just prior to eddy’s formation. Close to 100% of particles in the top 50 m of water in the eddy came from water which was located in the top 100 m on the continental shelf prior to the eddy formation. We also investigate the impact of 3 wind forcing scenarios: upwelling, downwelling and realistic winds. The hydrography of the continental shelf changes in response to the wind forcing, producing cooler or warmer surface temperatures. Despite the difference in wind forcing, an eddy still forms in each of the scenarios but, the path on which the eddy travels differs. The different scenarios also have different isothermal displacement. Interestingly, the maximum uplift of the 17⁰C isotherm is produced in the downwelling winds scenario. This study is the first of its kind to investigate CCE’s in the EAC and entrainment of shelf waters which can serve as biologically significant source of nutrients or seed populations.
Interaction between the Leeuwin Current and continental shelf along the Rottnest shelf and Perth Canyon

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The use of High-Frequency radar for measuring surface currents on continental shelves has been well established through development for over 30 years. The West Australian Integrated Marine Observing System (WAIMOS) has access to two HF Radar systems are operated by the Australian Coastal Ocean radar Network (ACORN): a WERA phased array system with shore stations located at Leighton Beach and Guilderton and a CODAR Seasonde beam-forming system with shore stations located at Seabird and Cervantes. These systems cover the coastal region from Cape Peron to Jurien Bay, extending up to 150 km offshore. The systems provide hourly values of surface currents on a regular grid with spacing of 4-6km. The WERA data have been analysed in detail to provide time-series consisting over 10,000 to provide information on seasonal variability and the interaction between the two major current systems: the Leeuwin and Capes currents with the latter present mainly during the summer months. The surface currents measured by the HF Radar together with coincident sea surface temperature images indicated the presence of several eddies, particularly within the Perth canyon. Here, a topographically trapped eddy was observed many times and appears to be a quasi-permanent feature. However this eddy migrates to the north and south of the canyon which leads to either upwelling or downwelling at the head of the canyon which was confirmed by a current mooring at the 200m contour. The presence of the eddy confirmed previous numerical modelling of the region which also predicted the presence of the eddy within the canyon. The surface currents also revealed the rapid changes in the current system through the passage of a continental shelf wave generated by Tropical Cyclone Bianca in January 2011.
The Leeuwin Current: the roles of topographic trapping, mixing, and advection in a buoyancy driven eastern boundary current

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$^3$International Pacific Research Center, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, Hawaii;
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The Leeuwin Current is a poleward eastern boundary current that is shelfbreak intensified. For a buoyancy driven basin, numerical experiments are used to investigate how shelf-slope topography, mixing, and advection contribute to an eastern boundary current's speed, transport, and spatial structure. The buoyancy forcing is composed of a meridional density gradient distributed over an upper layer depth. This density structure supports a near-surface eastward flow that converges over topography. The position where the upper layer intersects the slope sets the offshore width of the current by topographic trapping of Rossby waves. Vertical diffusion thickens the upper layer, strengthening the poleward current. Horizontal viscosity modifies the current width over which the zonal flow converges and hence controls the jet speed. Poleward density advection forms a cross-shelf density front, intensifying the poleward flow near the surface. Offshore density advection by frictionally driven, near-bottom flows can contribute to the jet’s frontal position near the shelf break.
Q-IMOS and eReefs: a Partnership to Monitor the Currents along the Great Barrier Reef

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A major goal of the Queensland Integrated Marine Observing System (Q-IMOS) seeks to understand the impact of the Coral Sea, in particular boundary currents and cool and warm water intrusion events on the Great Barrier Reef (GBR). These interactions can induce significant changes in the physical-chemical properties of the seawater of the lagoon impacting on its biodiversity and ecological health. In this context, four mooring pairs deployed along the continental slope, nominally in 200 – 300m of water together with a matching one on the outer continental shelf within the GBR matrix in depths of 30 to 70m.

A near-real time 4 km resolution three-dimensional hydrodynamic model covering the entire GBR and western Coral Sea is being developed under the eReefs project. Clear advantages of the model are the spatial coverage compared with the sparse observational network and the availability of near-real time data improves our ability understand and interpret events as they occur.

Severe Tropical Cyclone Yasi made landfall in northern Queensland, Australia on 3rd February 2011. It was the most powerful tropical cyclone to cross the Australian Coast in a century. As the system moved south-westwards towards the Australian coast, it passed near the Q-IMOS infrastructure located near the continental shelf break northeast of Townsville. This provided the opportunity to compare the observations of this extreme event with the eReefs model. Concurrent time series from the observations and model reveal low frequency events down to 200m are reproduced reasonably well resulting in observed warming of water at 200m by over 10°C. Longer period thermocline variability of the model is also in general agreement with the observations.

The eReefs project is a collaboration between the Great Barrier Reef Foundation, Bureau of Meteorology, Commonwealth Scientific and Industrial Research Organisation, Australian Institute of Marine Science and the Queensland Government (AIMS), supported by funding from the Australian Government’s Caring for our Country, the BHP Billiton Mitsubishi Alliance, and the Science Industry Endowment Fund. (source: http://www.barrierreef.org/OurProjects/eReefs.aspx). Q-IMOS GBR Moorings are operated and maintained by the AIMS and funded by the Queensland Government and the Australian Government’s National Collaborative Research Infrastructure Strategy and the Super Science Initiative. All observed data is made freely and openly available through the IMOS ocean data portal that is accessible from www.imos.org.au.
The Australian Bureau Of Meteorology’s Core Marine Observing Networks

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Observations of weather, ocean surface and sub-surface conditions are vital for ocean, weather and seasonal climate forecasting as well as for detecting global climate change.

The Australian Bureau of Meteorology operates a number of marine observing networks to provide data for day to day weather forecasting for the public and the marine user communities in Australia. The marine data collected by the Bureau are also distributed and used internationally as input to computer-based weather and ocean prediction systems, and support the seasonal scale climate prediction of events such as El Niño and La Niña in the Pacific. These data are also archived as a long-term record of how the world’s climate is changing.

This poster will describe the marine observing networks, additional observing platforms brought about through IMOS funding and their usage within and beyond the Bureau.